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Photovoltaic Manufacturing Technology Program

Final Subcontract Report
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INTRODUCTION

This final report is divided into five sections. Section 1, the Executive Summary, briefly describes the findings of the work performed under this contract. Section 2 is the statement of work, a description of the proposed work as defined in the initial contract. Several unanticipated events occurred during the execution of this contract and are detailed in this section. These events effected the main direction of the program. In Section 3, the results of an economic analysis performed on module manufacturing are given. These results were then used to give direction to the balance of the program and to provide guidance toward Phase II goals. Section 4 presents a brief description of a piece of equipment that will meet the needs of the industry, as determined in the financial section. Finally, in Section 5, our findings are summarized and conclusions are presented with future direction for the program.

SECTION 1

EXECUTIVE SUMMARY

Spire Corporation initiated Phase I of the SERI PVMaT program with several goals. These goals have been largely fulfilled during the contract period. During the course of this contract, we have examined several issues related to the manufacture of PV modules by Spire as well as the industry. We have shown that near-term cost competitive PV production will require the use of thin silicon wafers in the range of 200 microns thick. We also have shown that special production techniques for material of this thickness will be critical to achieving high yields; reduced product yield from present production methods with thin silicon eliminates the cost savings obtained by the increased utilization of silicon from thinner cells. However, when improved module production techniques are implemented, the yield can be improved and cost savings can be realized, as shown in Figure 1-1.

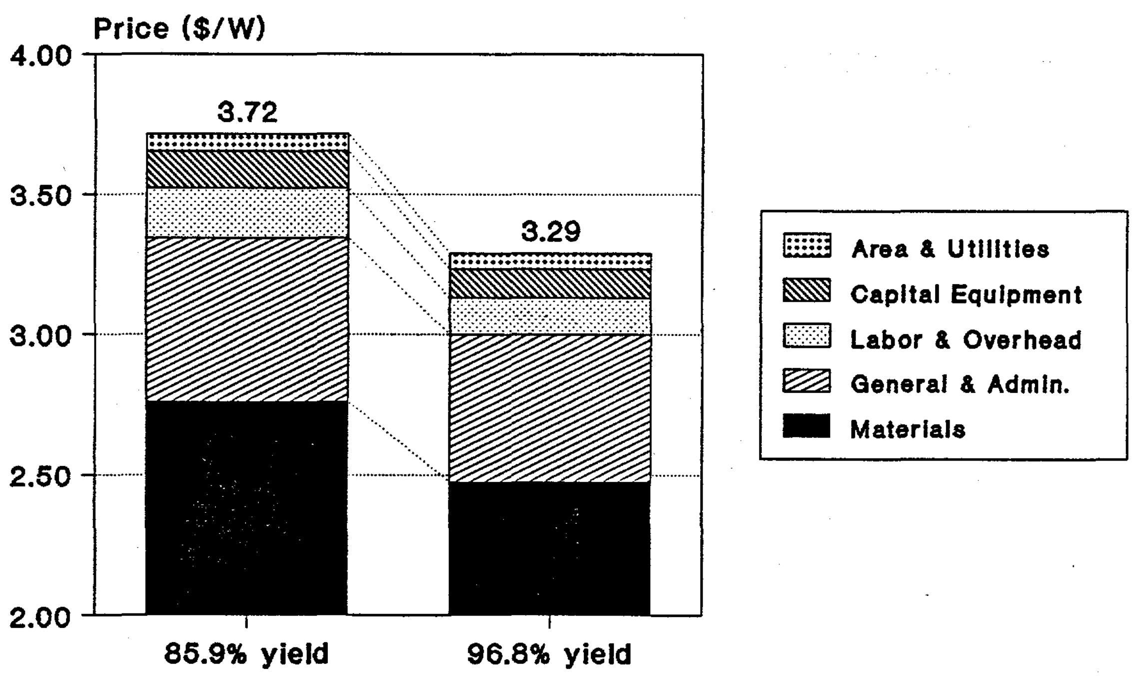

Figure 1-1. Effect of module line yield on module price at 10 MW/yr production level.

This fundamental problem of yield with thinner cells is clearly demonstrated in our financial analysis, Section 3. Unfortunately, one source of thin silicon that Spire was planning on using, Westinghouse Corporation, is no longer able to supply the materials. This leaves only one ribbon supplier for possible sourcing of the raw material to Spire for production. For this, and other reasons to be discussed later, Spire is not prepared to begin large-scale manufacture of PV modules.

Another goal of the program was to examine the equipment required to perform cost effective production of the modules. The financial results in Section 3 show that the tabbing and stringing are the most important functions of the module production process. Using the experience and knowledge gained from over ten years of manufacturing processing equipment, we have established the initial design of an interconnect machine. This initial machine design is detailed in Section 4. Specific components such as IPM operation are also presented in that section.

We have found that future development of this equipment will rely on cooperation with a module manufacturer. Therefore, Spire has discussed with several module manufacturers the potential of working together on the implementation and installation of this equipment. Establishing such a cooperative effort has been more difficult than anticipated due to the highly proprietary nature in which U.S. photovoltaic manufacturers approach the use of outside resources. The proposal for Phase II will detail this cooperation by outlining the scope of teaming and defining the goals to be attained in Phase II of the contract.

SECTION 2

STATEMENT OF WORK

The purpose of the PVMaT program is to encourage the growth of photovoltaic manufacturing in the United States. In keeping with this intent, Spire Corporation proposed to study two major items as part of their awarded Phase I contract. These two items were the expansion of module production by Spire and the utilization of next-generation equipment in module production.

2.1 PRODUCTION EXPANSION

The Phase I work at Spire focused on several objectives: determination of our present manufacturing capabilities and capacity, improvements in manufacturing techniques to lower costs, examination of barriers to the improvements, and cost estimates to remove those barriers.

Spire's original proposal called for a careful analysis of the module production capabilities at Spire. The company has produced modules at a limited scale in the past, for special projects and for customer demonstration purposes. A central point in the proposal was the importance of using thin silicon (<250 microns) in processing. The use of thin silicon reduces material cost associated with the wafers. We then intended to look at the use of the thin material for internal production of modules.

Two reasons dissuaded us from committing at this time to increased module production. The first was the specialized marketing and distribution requirements needed to sell the modules directly. Therefore, it was deemed more appropriate to service other manufacturers by providing modules to them to help in eliminating the pressure from insufficient capacity. During the latter part of 1990 and early 1991, it became apparent that existing manufacturing capacity could meet the reduced demand as the market softened. This left Spire with an unacceptable risk of not having a market for the modules it manufactured.

Another major factor in our decision to not expand manufacturing was the problem of silicon supply. In particular, our initial analysis on product cost was based on the thin silicon. Late in 1990, one of the organizations we were contemplating as a possible supplier stopped their production. This supplier, Westinghouse Corporation, had the capability of supplying some thin ribbon material for our production needs. The only other "non-captive" supplier for ribbon, Mobil Solar, was using its capacity in product. This was true for other organizations as well, since most manufacturers were only starting to look at use of the thin materials. While a hinderance to expanding production at Spire, it did lead to the next logical step of supporting the industry in equipment to handle the thin materials that manufacturers were moving toward. Another method of obtaining the thin materials was to produce our own, but the initial capital investment for growth and slicing equipment was prohibitive.

2.2 EQUIPMENT DEVELOPMENT

The second objective of the program was to examine the areas of cost-effective equipment development. This subject was extensively addressed during the course of the contract, with numerous meetings being held with the engineering staff to discuss this. An entire section of this report will detail the results of these discussions and meetings. Particular attention was given to the use of the thin cells; only module manufacturing issues were addressed as related to present technology. Results from the financial analysis were used to obtain the most cost sensitive area of production, then this area was addressed with thoughts towards our IPM (Intelligent Processing Machines) technology. The financial analysis, the bulk of the contract work, are presented in the next section.

SECTION 3

FINANCIAL ANALYSIS

The focus of our financial analysis was to determine how the cost of manufacturing silicon photovoltaic modules can be significantly reduced by examining the costs incurred at each step of module manufacturing. This section begins with a description of the module design chosen for this study (Section 3.1) followed by a description of module fabrication processes (Section 3.2). These sections provide background for the financial analysis discussed in Section 3.3.

3.1 MODULE DESIGN

The PV module is an assembly of electrically interconnected solar cells encapsulated in a weatherproof package to protect it from the terrestrial environment. The cells are fabricated on 10 cm x 10 cm silicon wafers. A module size of 63 cm x 124 cm was designed to accommodate 72 solar cells in a 6 cell x 12 cell field.

Many different types of modules are manufactured with Spire's equipment, including glass superstrate, double glass, substrate, and flexible designs. The module chosen for this analysis is the most common type, the glass superstrate design illustrated in Figure 3-1. Modules similar to this design have passed the stringent JPL Block IV and Block V environmental qualification tests.[1]

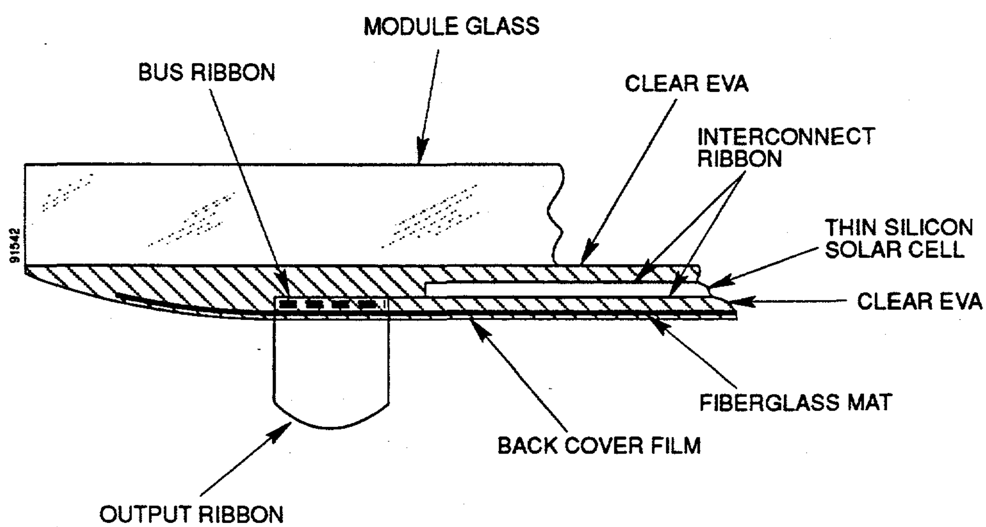

Figure 3-1. Cross section of Spire glass superstrate module.

The solar cells and their interconnecting ribbons are potted in a clear encapsulant based on the ethylene vinyl acetate (EVA) copolymer. A sheet of thermally tempered low-iron glass serves as the front cover and mechanical support for the cells. A porous fiberglass sheet is embedded in the EVA behind the cells to prevent abrasion of the cell circuit against the back cover during diurnal thermal cycling. The module back cover is a flexible, weatherproof, composite film composed of polyvinyl fluoride (PVF), polyester, and EVA. Two terminal boxes and an identification label are attached to the module's back surface.

3.2 MODULE FABRICATION PROCESS - PRESENT TECHNOLOGY

Spire's PV module production equipment is designed for integration into complete production lines. The most advanced of these lines presently available is the SPI-LINE™ 1000M, which has the capacity to produce 1 MW or more of modules per year in a single shift operation. The module production process flow used in the SPI-LINE 1000M is shown in Figure 3-2. Solar cells are either fabricated in a cell production line on site or purchased from an outside source.

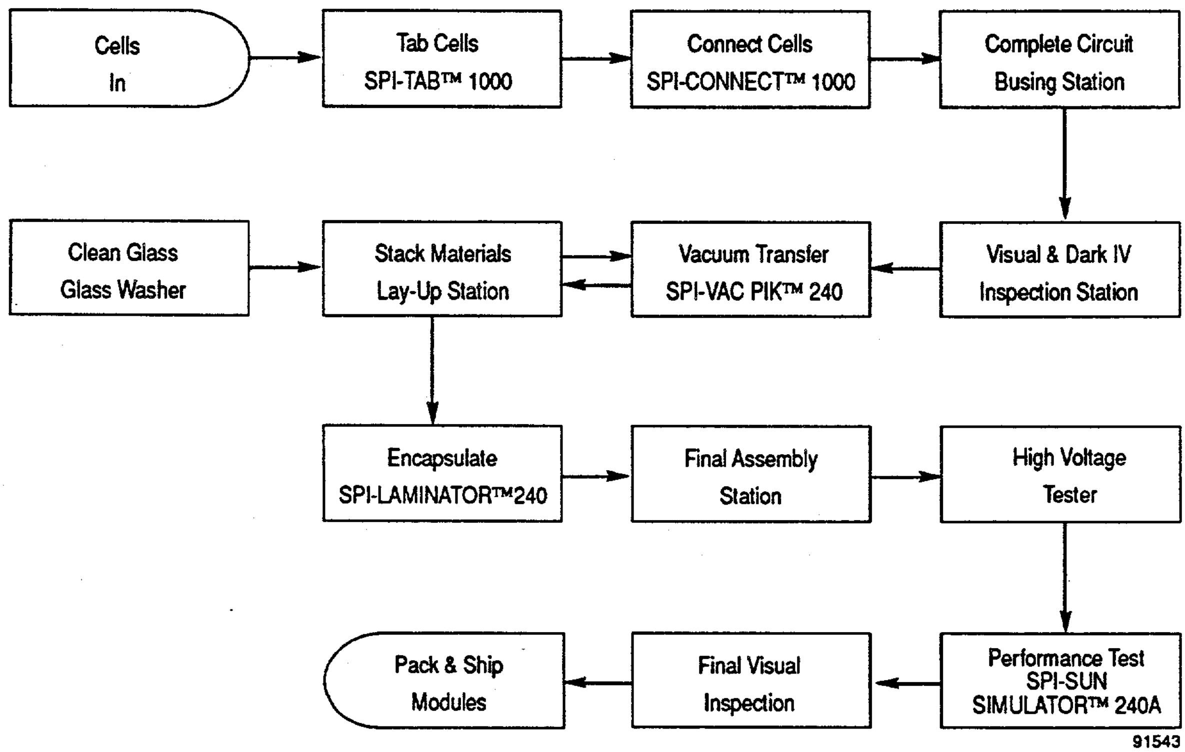

Figure 3-2. PV module production process sequence for the SPI-LINE 1000M.

3.2.1 Cell Tabbing

Two metal ribbon tabs are soldered to the front contact of each cell in the SPI-TAB™ 1000. The machine automatically feeds ribbon from two reels of interconnect stock, cuts it to length, makes a stress-relief bend in each cut ribbon (tab), places the two tabs on a cell, and solders them to the cell. The previous method of providing heat to the solder joint by conduction from heated soldering tips has been replaced by radiation from high intensity lamps. This non-contact method eliminates solder tip mechanical forces on the cell and eliminates the need to remove solder oxides from the tips. The cells are automatically loaded and unloaded with coin stack elevators which hold approximately 600 cells. The production rate is approximately seven seconds per cell.

3.2.2 Cell Interconnecting

Tabbed cells are visually inspected for proper tabbing and manually placed face down on a cell registration board which aligns all of the cells required for a module. The board is then placed in the SPI-CONNECT™ 1000 for cell back contact soldering. The soldering head, which utilizes the same high intensity lamps as the SPI-TAB 1000, is mounted on a carriage for X and Y positioning. The X-Y carriage is driven by stepper motors and lead screws for accurate placement over each cell. A programmable two-axis motor controller stores the cell locations and soldering cycle in non-volatile memory. When the module is finished, the registration board is removed from the SPI-CONNECT 1000. The production rate is approximately seven seconds per cell.

3.2.3 Circuit Completion

The module circuit is completed by the manual soldering of parallel bus ribbons and output ribbons.

3.2.4 Visual and Dark I-V Inspection

The module circuit is visually inspected prior to encapsulation to ensure that the workmanship and materials meet quality standards. A dark I-V test is done to check for proper electrical assembly.

3.2.5 Glass Cleaning

The module glass is thoroughly washed, rinsed, and dried in an automatic glass washing machine. The glass travels through the machine on a conveyor at speeds up to 7.3 meters per minute. The glass is cleaned with a hot water and detergent solution, rinsed with clean water, and dried with filtered high-velocity air.

3.2.6 Materials Lay-Up

The EVA, fiberglass, and back cover sheets are cut to size. These materials are assembled along with the cleaned glass and the interconnected cells to make the lay-up required for lamination. The SPI-VAC PIK™ 240 is a manually operated vacuum pick and place machine which transfers the interconnected cells from the registration board to the module lay-up.

3.2.7 Encapsulation

The interconnected cells are laminated between a glass superstrate and a flexible back cover sheet using modified EVA encapsulant. Modules are laminated and cured in an automatic process using the SPI-LAMINATOR™ 240. This equipment uses a programmed cycle of heat, vacuum, and pressure to remove the air, melt the EVA, conform the EVA to any irregular shapes, and crosslink the EVA. The cycle time is approximately seven minutes per module.

3.2.8 Final Assembly

The module edges are trimmed of excess EVA and back cover film. Two terminal boxes, one for each polarity, are attached with a waterproof adhesive. The module's bus ribbons are soldered to terminals in the boxes. These are manual operations.

3.2.9 High Voltage Isolation Test

This test identifies modules which might create a safety hazard when installed in an array. A high voltage tester is used to measure electrical isolation between the cell circuit and the module frame. Electrodes are attached to the frame and the shorted output leads of the module, a high voltage is applied, and leakage current is monitored.

3.2.10 Module Performance Test

Completed modules are tested under simulated sunlight to measure their electrical performance. The SPI-SUN SIMULATOR™ 240A uses a pulsed xenon light source with a spectral filter to closely match the solar spectrum (air mass 1.5 global conditions). An autoranging electronic load measures the module's complete I-V curve. A computer displays, prints, and stores all important data. The computer can correct I-V curves to other temperatures (such as Nominal Operating Cell Temperature). The computer also prints a label with a serial number and module-specific performance data which is attached to the back of each module.

3.2.11 Final Inspection

Each completed module is visually inspected to ensure that the workmanship and materials meet quality standards.

3.3 FINANCIAL ANALYSIS FOR 10 MEGAWATT MODULE MANUFACTURING

The preceding section (3.2) describes PV module processing for Spire's current manufacturing line. The throughput of that line is approximately 1 MW/yr for a single shift operation (8 hrs/day, 5 days/week). The financial analysis done for this program assumed a 10 MW/yr, three-shift operation (24 hrs/day, 5 days/week) to obtain economies of scale. Three versions of this 10 MW/yr operation have been analyzed in detail:

Case 1. Present manufacturing methods are used (as described in Section 3.2) but the quantities of equipment, labor, and materials are scaled up to obtain 10 MW/yr throughput. The silicon wafer thickness is 300 µm, a practical lower limit for Cz-Si sliced by conventional ID saws.

Case 2. Present manufacturing methods scaled to 10 MW/yr are used, as described in Case 1. A thinner 200 µm silicon wafer (either ribbon Si or Cz-Si sliced by wire saws) reduces cell costs, but module yield drops as a consequence.

Case 3. A thin 200 µm silicon wafer is used, as in Case 2, but improved module manufacturing methods are introduced to increase yields.

A list of parameters assumed for all three cases is provided in Table 3-1. The wafer diameter is 125 mm which is cropped to form a 100 mm square; the resulting cell area is 97 cm^2. The cell efficiency is assumed to be 14.5%, a value which can be obtained in production from such features as a textured, passivated, antireflection coated front surface, a low-shadow printed silver grid, and an aluminum back surface field. A diagram of the cell cross section is provided in Figure 3-3.

Table 3-1. Module manufacturing assumptions.

Parameter	Value	Unit
Cz-Si diameter	125.0	mm
Si cropped square	100.0	mm
Cell area	97.0	cm^2
Cell efficiency	14.5	%
Cells/module	72	each
Packing factor	87.0	%
Module efficiency	12.6	%
Module line up-time	95.0	%
Module line output	10	MW/yr

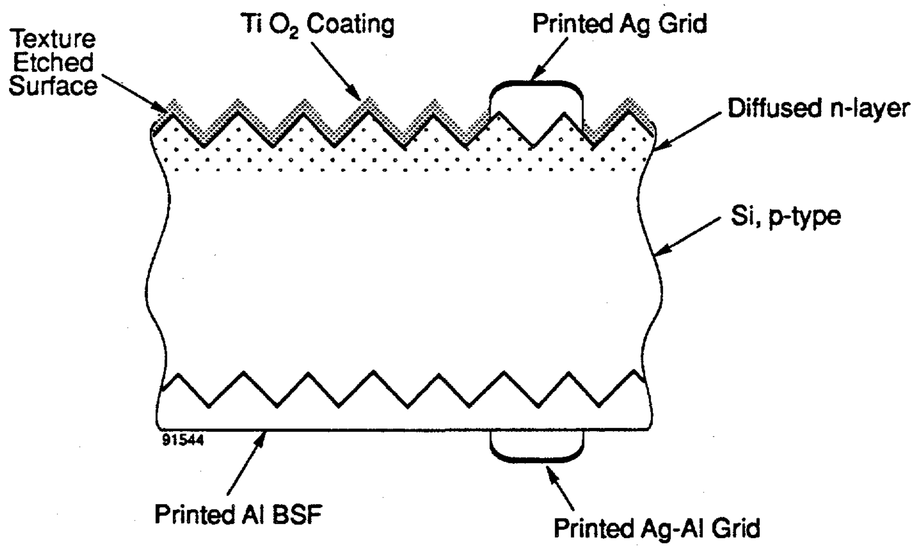

Figure 3-3. Cz-Si cell cross section (not to scale).

Each step of each of the three cases was analyzed for equipment throughput, labor content, and materials consumption. Adjustments were made to these factors as required to satisfy the 10 MW/yr production output. The results of these three case studies are provided in the following sections.

3.3.1 Case Study No. 1: 300 μm Cz-Si, Present Manufacturing Methods

The manufacturing methods for this case are the same as those used presently and described in Section 3.2. The solar cells are fabricated from 300 μm (0.012 inch) thick Cz silicon wafers. Using the assumptions given in Table 3-1 and an estimated 96% process yield, the cell and module power and required process throughput have been calculated. The results are presented in Table 3-2.

The equipment throughput (known from present processing experience) was compared to the 10 MW/yr throughput requirements for each step of the module line process. The quantities of each equipment needed to meet the 1246 cells per hour throughput rate was determined. The results are listed in Table 3-3.

The labor needed to produce 10 MW/yr of modules was estimated, given the processing rate (Table 3-2) and the equipment (Table 3-3). Each process step was broken down into individual operations for estimating both the labor times (seconds/cell) expended and the cell yields. Labor times were then consolidated into blocks that could be assigned to specific operators. The resulting labor and cell yield numbers are summarized in Table 3-4. The cumulative yield of 95.9% was computed by multiplying the yields of each individual operation together.

Table 3-2. 10 MW/yr cell and module throughput; 300 μm Si, present manufacturing methods.

Parameter	Value	Unit
Power/cell	1.41	W
Power/module	101.27	W
Factory output	98,503	modules/yr
	7,092,199	cells/yr
Module line yield	96	%
Factory input	7,385,212	cells/yr
Module line up-time	5,928	hrs/yr
Module line throughput	1,246	cells/hr
	17.3	modules/hr

Table 3-3. Equipment needed to produce 10 MW/yr using present manufacturing methods.

Step	Equipment	Quantity
1	SPI-TAB 1000	3
2	SPI-CONNECT 1000	3
3	Bussing station	2
4	Inspection station	1
5	Glass washing system	1
6	Lay-up station	3
7	SPI-VAC PIK 240	1
8	SPI-LAMINATOR 240	2
9	Assembly Station	2
10	High Voltage Tester	1
11	SPI-SUN SIMULATOR	1

Table 3-4. 10 MW/yr module line labor and cell yield estimates for 300 µm Si, present methods.

Step	Operation	No. of Operators per Shift	Cell Yield (see note)
1. Tab	Load ribbon & cells Tabber auto process Unload tabbed cells	1.0	99.9 99.0 99.9
2. Connect	Load cells on board Load board Connect auto process Unload board	4.0	99.0 100.0 99.0 100.0
3. Bus	Cut bus ribbon Solder bus ribbon	2.0	100.0 100.0
4. Inspect	Electrical test Visual inspection	1.0	100.0 100.0
5. Clean glass	Load & unload glass	0.2	100.0
6. Lay-up	Cut EVA (2 layers) Cut fiberglass Cut back cover Lay-up w/ glass, cells	2.6	100.0 100.0 100.0 99.5
7. Laminate	Load laminator Lam. auto process Unload laminator Trim module edges	1.0	100.0 99.5 100.0 100.0
8. Final assembly	Attach output boxes Solder bus ribbons	2.0	100.0 100.0
9. Hi-V test	Hi-V isolation test	1.0	100.0
10. Perf. test	Perf. test & label Final visual inspect	1.0	100.0 100.0
11. Pack	Pack in carton	0.2	100.0
	Total Operators:	**16.0**	
	Cumulative Yield:		**95.9**

Note: Yield is % of cells surviving each step. Inspections identify but do not cause loss.

It can be seen from the yield numbers of Table 3-4 that while the cell yield is 96% for the entire process, most of the yield loss occurs in steps 1 and 2, cell tabbing and interconnecting. Thus the materials quantities were increased by 4% for cells and interconnect ribbons, while they were increased by 1% for all other module materials.

Materials cost quotations were obtained for the required quantities from vendors of low-iron glass, EVA encapsulant, back cover film, interconnect and bus ribbon, fiberglass, output boxes, and other miscellaneous materials. The module is designed to be frameless, in line with current trends to reduce module cost.[2] Material costs (excluding cell cost) amount to $0.25/W, including yield loss. The cost breakdown is shown in Figure 3-4.

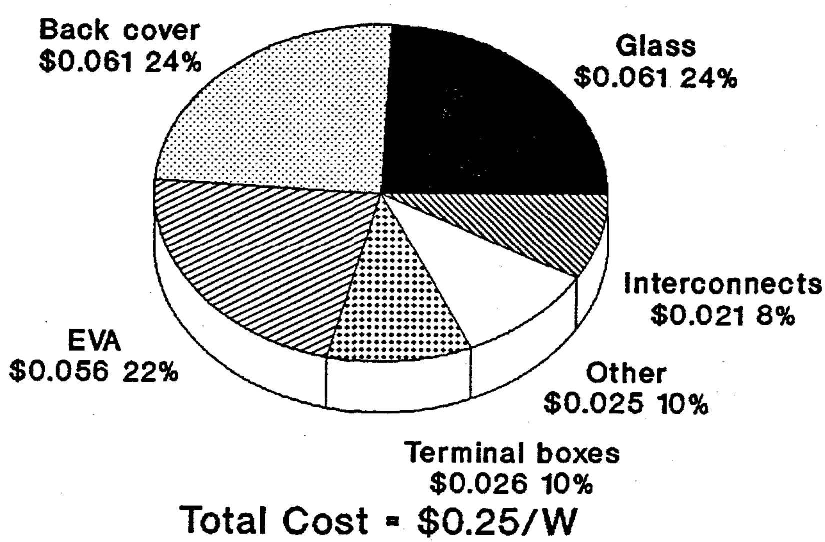

Figure 3-4. Module materials costs ($/W), excluding cells.

Solar cell cost was estimated using Spire's internally developed costing model, the Investment Analysis - Commercial Model (IACM). The IACM model was provided with detailed materials, labor, and capital equipment cost data for Cz ingot growth, ID saw wafer slicing, and solar cell processing. At the 10 MW/yr production level, the IACM model projects cell cost to be $2.53/W, including yield losses incurred by the module line. (The IACM model includes a 12% return on equity (ROE) as part of the $2.53/W cost.) Figure 3-5 illustrates how the cell cost clearly dominates the module materials costs, at 91% of the total.

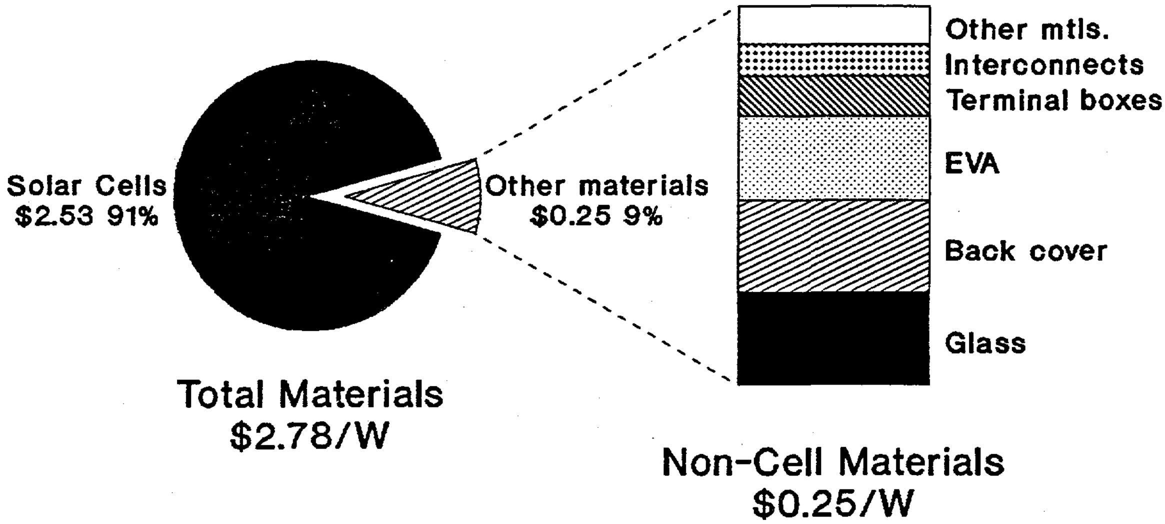

Figure 3-5. Total module materials cost ($/W). Present manufacturing methods, 300 μm Si.

Module selling price was estimated using the Jet Propulsion Laboratory's Improved Price Estimation Guidelines (IPEG) model.[3] Input provided to the IPEG model includes the following items discussed previously in this section: cell cost, other module materials costs, number of operators, and capital equipment costs. Additional input includes the production floor area requirements and the utilities requirements. An operator labor rate of $9.00/hr and a five year equipment amortization period were selected. IPEG imposes a 100% overhead rate on labor and a 21% G&A rate on materials and utilities costs.

The IPEG model projects a module selling price of $3.73/W. Materials and associated G&A expenses are responsible for 90% of the total price, as shown in Figure 3-6. Capital equipment expenses contribute 3.6% to the total price; labor and overhead contribute 2.4% each; area related expenses 1.2%; and utilities and associated G&A 0.5%. The capital equipment expense includes a high amortization rate (0.59 times the equipment cost for a five-year period) because it includes a 21% ROE.

3.3.2 Case Study No. 2: 200 μm Cz-Si, Present Manufacturing Methods

The manufacturing methods for Case 2 are identical to those assumed for Case 1 discussed in Section 3.3.1 above. The solar cells, however, are fabricated from thinner 200 μm silicon. Such silicon may be fabricated by a ribbon process in production quantities at some future date. Cost savings are expected to be gained from the ribbon process by the elimination of wafer slicing, which consumes approximately 50% of a silicon ingot in the form of kerf loss.

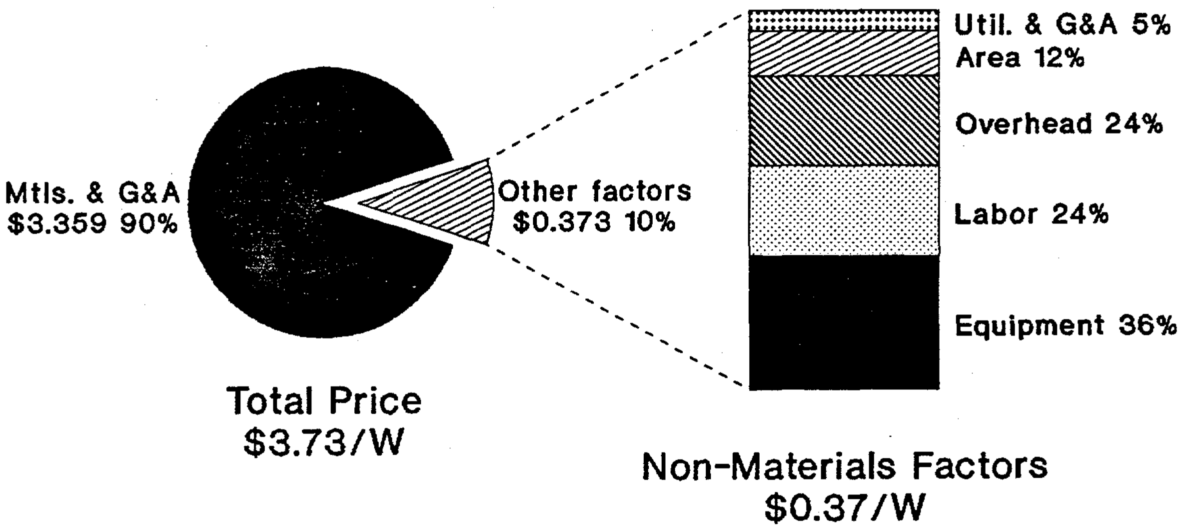

Figure 3-6. Module price ($/W) for present manufacturing methods and 300 μm Cz-Si.

While the ribbon-Si approach is an attractive option, the current low level of commercial ribbon production and the lack of available cost data make an accurate financial analysis difficult. Therefore, a different approach was selected for analysis: Cz-Si sliced by wire saws. In this approach, the number of wafers obtained from a silicon ingot is increased (compared to the number obtained by I.D. sawing) by the ability to saw a thinner (200 μm) wafer and also by a reduction in kerf loss (only 200 μm vs. 300 μm). Thus, wire sawing can produce a single wafer from 400 μm of Cz ingot, while I.D. sawing requires 600 μm or more per wafer.

Present module manufacturing methods will exhibit decreased product yields with thinner Si, particularly for the process steps prior to lamination. Cell yield numbers are presented for each step in Table 3-5. The cumulative yield is 85.9%.

Using the manufacturing assumptions listed in Table 3-1 and the 85.9% cell yield from Table 3-5, the required process throughput has been calculated. The results are presented in Table 3-6.

While the cell yield is 85.9% for the entire process, most of the yield loss occurs in steps 1 and 2, cell tabbing and interconnecting. Thus the materials quantities were increased by 16.4% (i.e., divided by 0.859) for cells and interconnect ribbons and increased by 2.0% for all other module materials. Material costs (excluding cell cost) amount to $0.25/W, including yield loss.

Table 3-5. 10 MW/yr module line labor and cell yield estimates for 200 μm Si, present methods.

Step	Operation	No. of Operators per Shift	Cell Yield (see note)
1. Tab	Load ribbon & cells Tabber auto process Unload tabbed cells	1.0	99.0 95.0 99.0
2. Connect	Load cells on board Load board Connect auto process Unload board	4.0	98.0 100.0 96.0 100.0
3. Bus	Cut bus ribbon Solder bus ribbon	2.0	100.0 100.0
4. Inspect	Electrical test Visual inspection	1.0	100.0 100.0
5. Clean glass	Load & unload glass	0.2	100.0
6. Lay-up	Cut EVA (2 layers) Cut fiberglass Cut back cover Lay-up w/ glass, cells	2.6	100.0 100.0 100.0 99.0
7. Laminate	Load laminator Lam. auto process Unload laminator Trim module edges	1.0	100.0 99.0 100.0 100.0
8. Final assembly	Attach output boxes Solder bus ribbons	2.0	100.0 100.0
9. Hi-V test	Hi-V isolation test	1.0	100.0
10. Perf. test	Perf. test & label Final visual inspect	1.0	100.0 100.0
11. Pack	Pack in carton	0.2	100.0
	Total Operators:	**16.0**	
	Cumulative Yield:		**85.9**

Note: Yield is % of cells surviving each step. Inspections identify but do not cause loss.

Table 3-6. 10 MW/yr cell and module throughput; 200 μm Si, present manufacturing methods.

Parameter	Value	Unit
Power/cell	1.41	W
Power/module	101.27	W
Factory output	98,503	modules/yr
	7,092,199	cells/yr
Module line yield	85.9	%
Factory input	8,260,745	cells/yr
Module line up-time	5,928	hrs/yr
Module line throughput	1,394	cells/hr
	19.4	modules/hr

The IACM model was run, substituting wire saws for I.D. saws, to determine the cell cost. The cell cost dropped from \$2.43/W (I.D. sawn silicon, Case 1) to \$2.16/W (wire sawn silicon, Case 2), an 11% decrease. These are the cell costs without regard to module line yield; i.e., they are the cell costs if module yield were 100%. When module line yield is factored into both cases, however, the increase in cell quantities required to maintain a 10 MW/yr output results in a cell cost drop of only 0.5%, from \$2.530/W to \$2.516/W. Thus the cost saved by using thinner silicon is largely negated by the decreased yield in processing thinner cells in the module line. The materials costs are shown graphically in Figure 3-7.

Equipment throughput was compared to the processing requirements of Case 2, as summarized in Table 3-6. The quantities of equipment required for Case 1 (listed in Table 3-3) were found to have sufficient capacity for Case 2.

Labor requirements were also estimated for Case 2, given the processing rate and the equipment. The number of operators required per shift are listed in Table 3-5. The increased throughput required for Case 2 (by the reduced yield) was found to be small enough that the number of operators does not need to be increased over the Case 1 level. This is true because the calculated labor time was consolidated into blocks for assignment to specific (whole number) operators, as would be done in an actual production line. Thus the calculated times for a specific step are generally some fraction of an operator less than the number of operators assigned to that step.

Module selling price was estimated using the JPL IPEG model in the same manner described for Case 1 (Section 3.3.1). IPEG projected a selling price of \$3.72/W for Case 2. Materials and associated G&A expenses contribute 90% of the total Case 2 price. The distribution of expenses is shown in Figure 3-8.

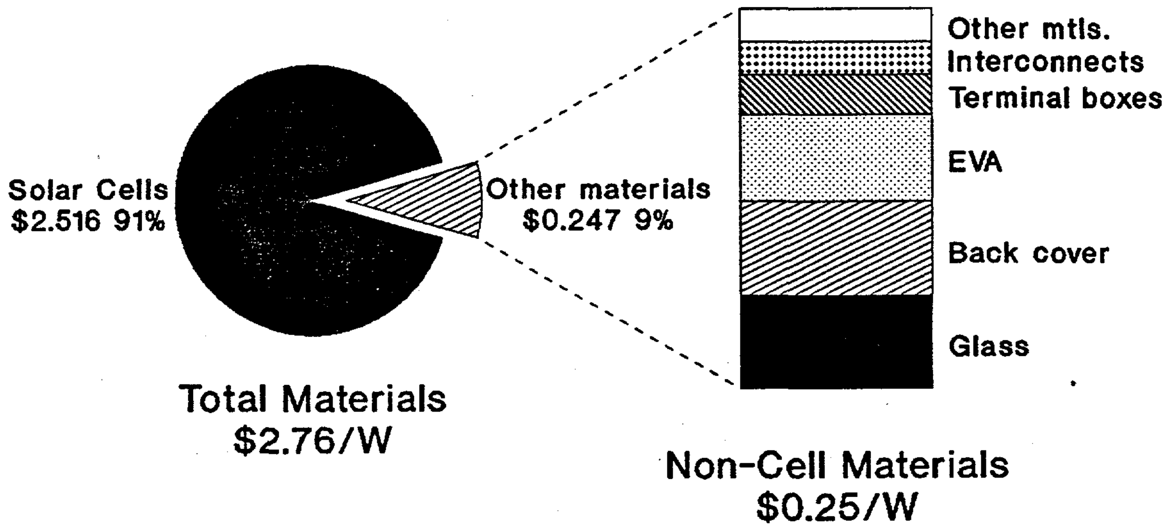

Figure 3-7. Module materials cost ($/W). Present manufacturing methods, 200 μm Si.

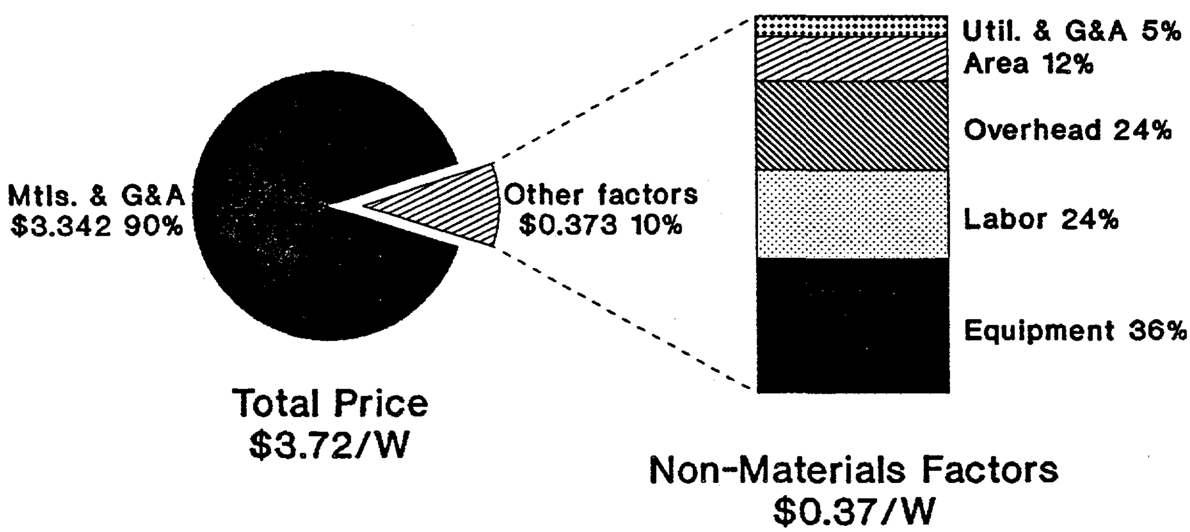

Figure 3-8. Module price ($/W) for present manufacturing methods and 200 μm Cz-Si.

3.3.3 Case Study No. 3: 200 μm Cz-Si, Improved Manufacturing Methods

The previous two case studies (Sections 3.3.1 and 3.3.2) have shown that decreasing the silicon thickness from 300 μm to 200 μm increases the solar cell yield loss in the module line. This is illustrated by Figure 3-9, which shows the number of cells per year lost in each step (for steps that have less than 100% yield). As a result, Case 3 considers a scenario in which the manufacturing methods have been improved to allow the module line to process lower cost, thinner solar cells without paying the penalty of markedly decreased yields.

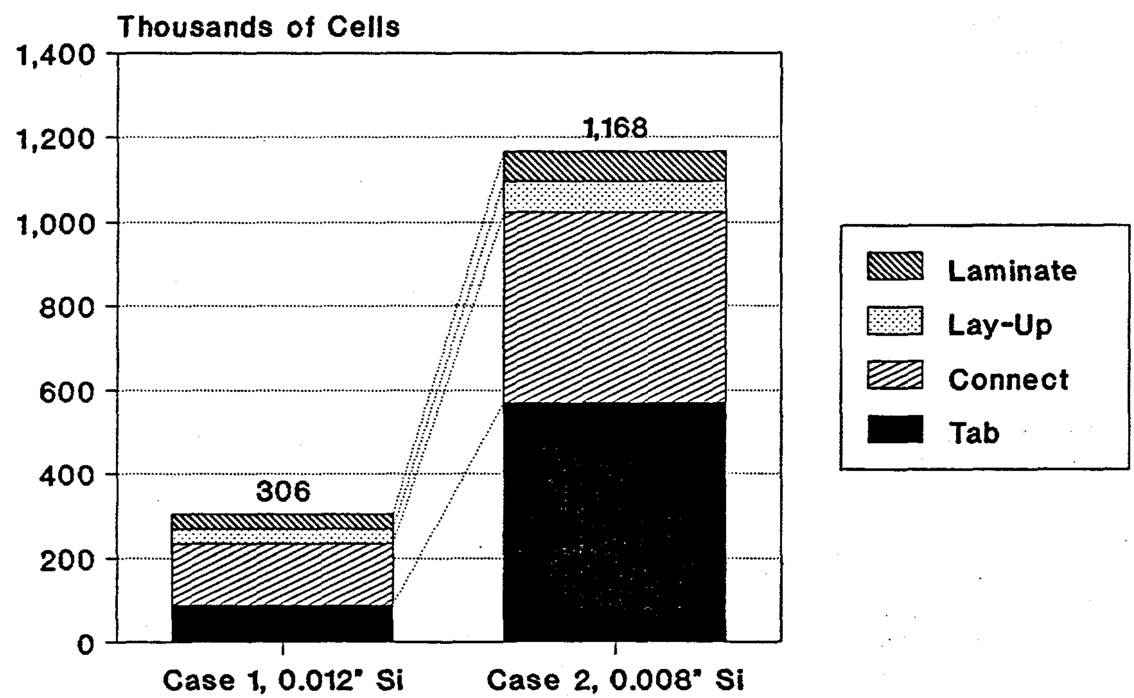

Figure 3-9. Cell yield loss per year by process step for present manufacturing methods (Cases 1 and 2).

It is clear from Figure 3-9 that a vast majority of the yield loss stems from the tabbing and interconnecting operations used by present manufacturing techniques. In fact, 88% of the yield loss in Case 2 is attributed to these steps, as shown in Figure 3-10.

Based on this analysis, our Case 3 scenario replaces the current tabbing and interconnecting operations with a new approach which significantly reduces mechanical and thermal stresses on the cells. This approach, described in more detail in Section 4, merges the tabbing and connecting equipment into one fully automated machine. The two separate soldering operations now done on two machines is replaced by a single soldering step in which front and back interconnections are made simultaneously. The new machine also eliminates the manual loading of tabbed cells onto alignment boards prior to interconnection. These and other improvements incorporated into the proposed equipment are expected to significantly increase the yield and throughput of the cell interconnecting process while reducing labor content.

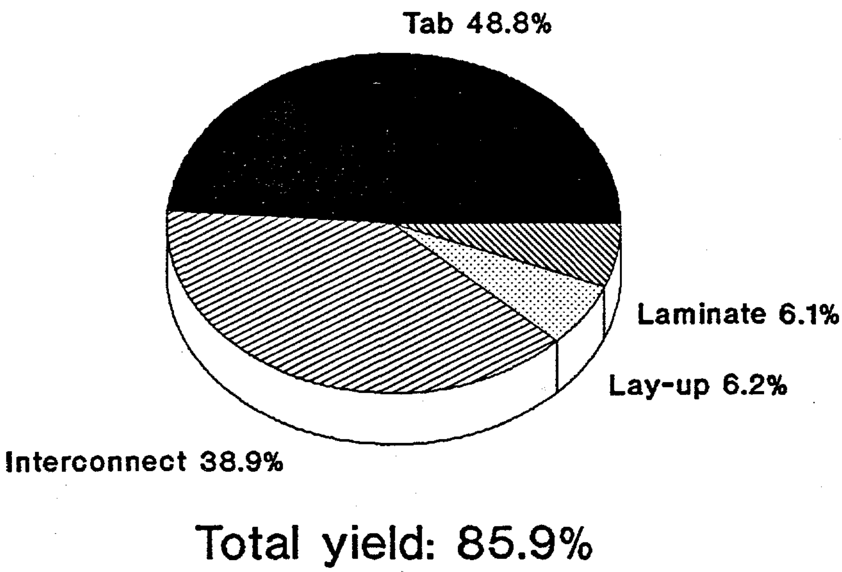

Figure 3-10. Yield loss by process step for 200 μm silicon, present methods (Case 2).

Projected cell yield numbers are presented by process step in Table 3-7. Since only the tabbing and interconnecting processes have been modified, the yield in the lay-up and lamination steps is the same as for Case 2 (Table 3-5). The cumulative yield is 96.8%. Labor requirements are also listed in Table 3-7. Due to increased automation, the four operators previously required to load alignment boards (Cases 1 and 2) have been eliminated.

The required process throughput was calculated using the manufacturing assumptions listed in Table 3-1 and the 96.8% cell yield from Table 3-7. The results are presented in Table 3-8.

The materials quantities were increased by 3.3% (i.e., divided by 0.968) for cells and interconnect ribbons and increased by 2.0% for all other module materials. Material costs (excluding cell costs) amount to $0.245/W including yield loss. Cell cost prior to adjustment for module line yield was obtained from the IACM model run for Case 2: $2.16/W. When module yield is factored in, the cell cost increases to $2.231/W. The total materials cost is $2.48/W as shown in Figure 3-11.

Equipment throughput was compared to the processing requirements summarized in Table 3-8. The projected throughput of the improved interconnection equipment (called the "SPI-ASSEMBLER 5000") was estimated. The quantities of equipment required for this case are listed in Table 3-9.

Table 3-7. 10 MW/yr module line labor and cell yield estimates for 200 μm Si, improved methods.

Step	Operation	No. of Operators per Shift	Cell Yield (see note)
1. String cells	Load ribbon & cells Auto stringing Auto board loading Unload board	1.0	99.9 99.0 99.9 100.0
2. Bus	Cut bus ribbon Solder bus ribbon	2.0	100.0 100.0
3. Inspect	Electrical test Visual inspection	1.0	100.0 100.0
4. Clean glass	Load & unload glass	0.2	100.0
5. Lay-up	Cut EVA (2 layers) Cut fiberglass Cut back cover Lay-up w/ glass, cells	2.6	100.0 100.0 100.0 99.0
6. Laminate	Load laminator Lam. auto process Unload laminator Trim module edges	1.0	100.0 99.0 100.0 100.0
7. Final assembly	Attach output boxes Solder bus ribbons	2.0	100.0 100.0
8. Hi-V test	Hi-V isolation test	1.0	100.0
9. Perf. test	Perf. test & label Final visual inspect	1.0	100.0 100.0
10. Pack	Pack in carton	0.2	100.0
	Total Operators:	**12.0**	
	Cumulative Yield:		**96.8**

Note: Yield is % of cells surviving each step. Inspections identify but do not cause loss.

Table 3-8. 10 MW/yr cell and module throughput; 200 μm Si, improved manufacturing methods.

Parameter	Value	Unit
Power/cell	1.41	W
Power/module	101.27	W
Factory output	98,503	modules/yr
	7,092,199	cells/yr
Module line yield	96.8	%
Factory input	7,323,932	cells/yr
Module line up-time	5,928	hrs/yr
Module line throughput	1,235	cells/hr
	17.2	modules/hr

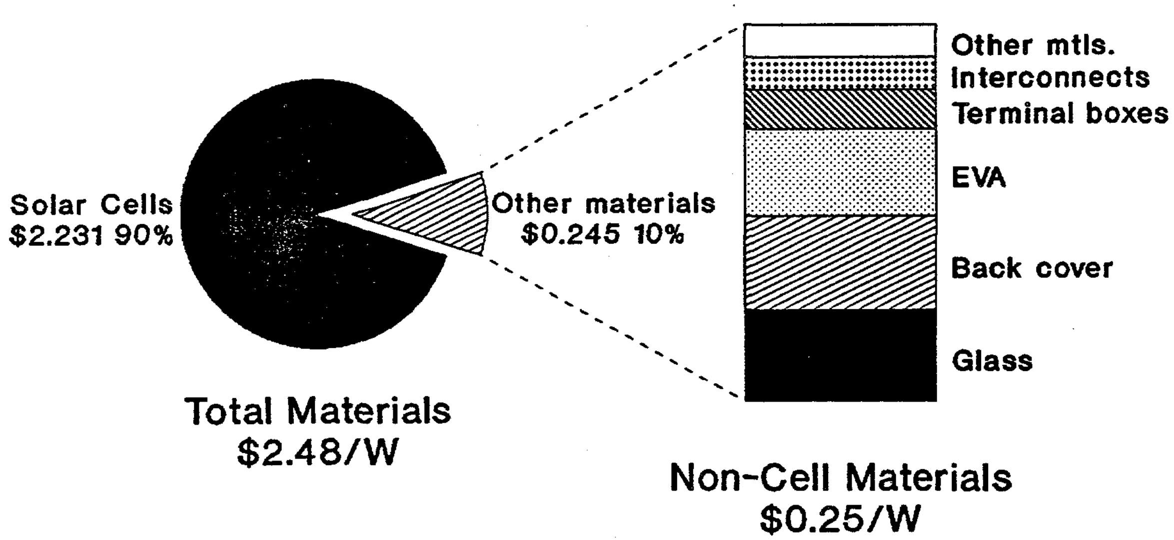

Figure 3-11. Module materials cost ($/W). Improved manufacturing methods, 200 μm Si.

Table 3-9. Equipment needed to produce 10 MW/yr using improved manufacturing methods.

Step	Equipment	Quantity
1	SPI-ASSEMBLER 5000	2
2	Bussing station	2
3	Inspection station	1
4	Glass washing system	1
5	Lay-up station	3
6	SPI-VAC PIK 240	1
7	SPI-LAMINATOR 240	2
8	Assembly Station	2
9	High Voltage Tester	1
10	SPI-SUN SIMULATOR	1

Module selling price was estimated using the JPL IPEG model in the same manner described for Case 1 (Section 3.3.1). IPEG projected a selling price of \$3.29/W for Case 3. Materials and associated G&A expenses contribute 91% of the total Case 3 price. The distribution of expenses is shown in Figure 3-12.

3.3.4 Case Study Findings

The financial analysis reported in the preceding sections has shown that cells made from thinner silicon may cost less to produce, but they cannot reduce module cost unless cell yield is controlled in the module line. A summary of the financial analysis is provided in Table 3-10. The cost of solar cells fabricated from Cz-Si was calculated using the Spire developed IACM model. The cost of 200 μm cells was less, at \$2.16/W, than the cost of 300 μm cells, at \$2.43/W, prior to accounting for module line yield. However, the increased yield loss with thin cells for present manufacturing methods essentially negates the decrease in cell cost. This is seen by comparing the module cost in Case 1, at \$3.73/W, with Case 2, at \$3.72/W. When manufacturing methods are improved to reduce yield loss, as in Case 3, the benefits of lower cost thin cells can be preserved; module cost is reduced to \$3.29/W.

Figure 3-13 shows how many cells are lost per year for the three cases analyzed. Present module manufacturing technology is expected to produce a yield loss of 306,000 cells per year when 300 μm Si is used (Case 1). Reducing the Si thickness to 200 μm increases the yield loss to more than one million cells per year (Case 2). Recommended improvements in the cell tabbing and interconnecting processes will reduce the thermal and mechanical stresses on the cells and also reduce the amount of manual handling. These improvements are expected to bring the yield loss of thin cells down to the 232,000 cells per year level (Case 3).

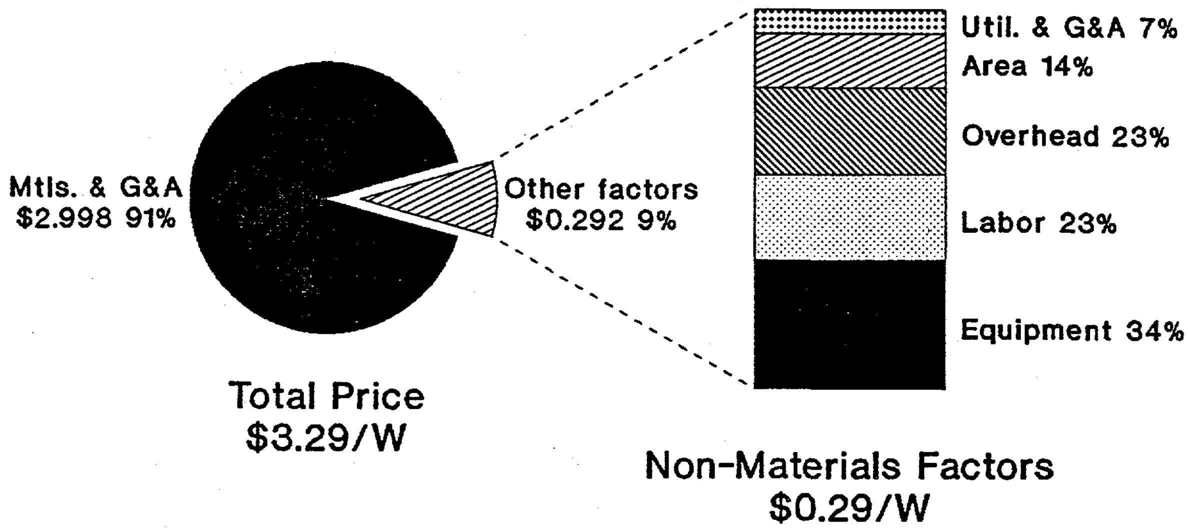

Figure 3-12. Module price ($/W) for improved manufacturing methods and 200 μm Cz-Si.

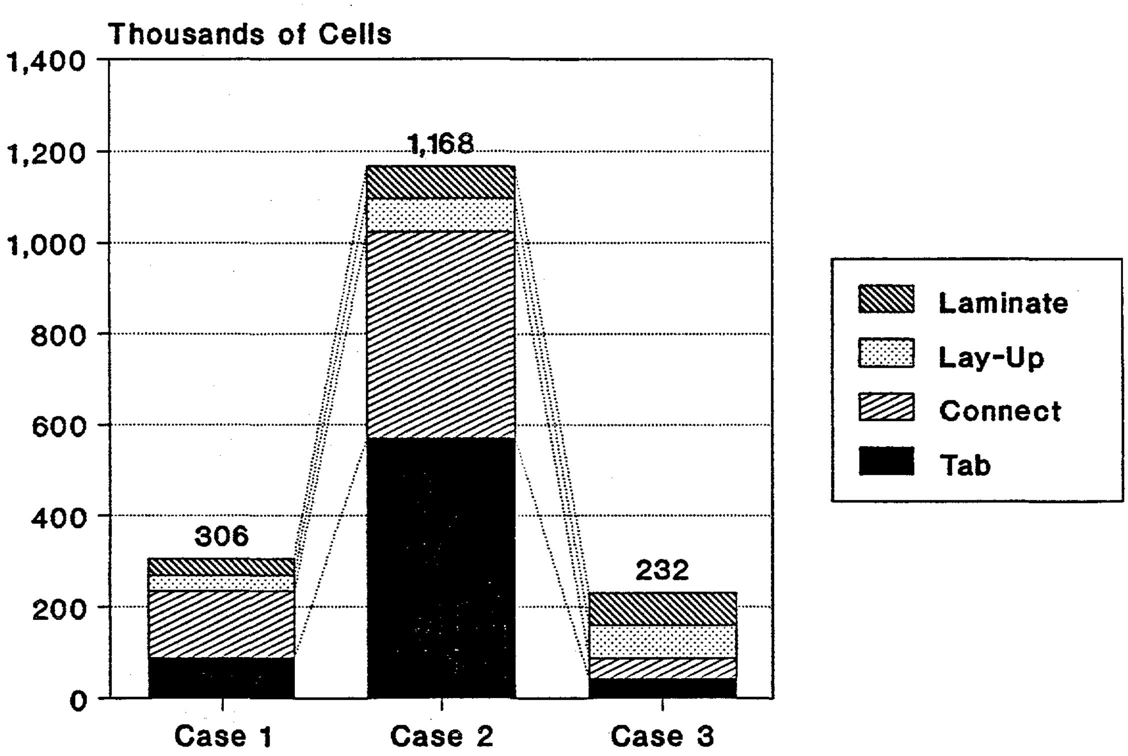

Figure 3-13. Cell yield loss per year for the three case studies.

The cell yield loss data of Figure 3-13 and the cell cost data from the IACM analysis were used to calculate the cost of the yield loss. As shown in Table 3-10, $1.0M/yr is lost to yield in Case 1, $3.6M/yr is lost in Case 2, and $0.7M/yr is lost in Case 3.

Table 3-10. Summary of 10 MW/yr financial analysis.

	Case 1	**Case 2**	**Case 3**
Manufacturing methods	Present	Present	Improved
Cz-Si thickness (μm)	300	200	200
Cell cost ($/W)	2.43	2.16	2.16
Yield loss (%)	95.9	85.9	96.8
Module cost ($/W)	3.73	3.72	3.29
Yield loss (cells/yr)	306,000	1,168,000	232,000
Cost of cell loss ($/yr)	1,048,000	3,557,000	707,000

SECTION 4

INTERCONNECT EQUIPMENT

As described in Section 2 of this report, a goal of the program was to determine the equipment requirements for advanced module production. Section 3 points out the limitations of present day technology when dealing with cells fabricated from the thin silicon wafers or ribbon. Problems with yield, aggravated at the 10 MW throughput levels, led us to examine the cell tabbing and stringing equipment.

4.1 EQUIPMENT DESIGN GOALS

Consideration to machine design was given in several areas: throughput, alignment, cell handling, ribbon preparation and delivery, ribbon to cell connection method, and string handling. For purposes of flexibility, the machine would be modular in nature and communications between the different modules would utilize a proven system, such as the Semiconductor Equipment Communications Standard (SECS).

4.2 EQUIPMENT DESIGN CONCEPTS

The question of machine throughput design was considered. A balance was struck between present throughput and goals that were unrealistically high. This balance considered that present designs at the one to two megawatt per year level are insufficient to handle the factories being put on line today. While there is great hope for the future expansion of the PV manufacturing, in the near term (three years) there is little discussion of expansion beyond five megawatt increments. For this reason the machine throughput criterion was set to nominally handle five megawatts per year, which corresponds to one cell every four seconds (based on realistic cell efficiencies for 100 cm^2 cells). The allowable cell size is flexible, up to 150 cm by 150 cm size.

To minimize the mechanical handling and thermal shock on thin cells, a one-pass interconnect system was devised. This system would connect ribbons to the front and back of a cell with one operation. To minimize the turning of cells, the machine was designed to align the cell patterns with the grid side face down. The cells would therefore be located on a transparent X,Y,Θ vacuum table, with an "up-looking" pattern recognition system. This system would then align the cells in preparation for ribbon placement on the cells.

The ribbon preparation consists of cutting, stress relief forming, and fluxing two parallel ribbons. The success of our ribbon forming and delivery system on our SPI-TAB 1000 machine led us to choose a similar ribbon handling system, with the addition of a flux roller system. The ribbon is unwound off the storage reel into an accumulator bin. It is then pulled through the flux station, has a stress relief bend mechanically formed, and is cut to length. The prepared ribbon is then placed on the aligned cell.

The cells are moved either in a linear manner on belts or by a vacuum pick-up when more precise movement is required, such as between the cell alignment and the ribbon delivery area.

Once at the ribbon delivery area the cells are placed on moving vacuum tables. The tables hold down the cells and ribbons for joining, as well as move the cells on a fixed surface as strings are fabricated.

The ribbon connection method was envisioned to be flexible with such methods as ultrasonic welding or thermal soldering considered. Again based on the success of our SPI-TAB 1000, the machine incorporates our infrared light soldering method. This method heats the cells, usually along the ribbon area, using high intensity lamps and very light force spring clips to hold down the solder-tinned ribbon during the reflow process. We have performed experiments that prove the feasibility of this technique for simultaneous front and back surface soldering of interconnect ribbons to cells. The modular nature of the machine would allow other joining methods, such as ultrasonic bonding, to be incorporated.

After the cells are interconnected, a special vacuum arm picks up the string of cells and places them onto the stringing table. This arm can turn 180° so that strings may be easily series connected.

The entire machine would be controlled by a master computer, with the module under local SECS control. This would allow such modifications as cell size and grid pattern, ribbon length and placement, and string lengths to be made with software commands.

The preliminary machine design incorporated many of our thoughts on advanced processing and handling. It was designed from the basis of seven years of tabbing experience.

SECTION 5

CONCLUSIONS

The work performed in this contract has been focused on two areas: economic analysis of present module manufacturing methods, and the conceptualization of advanced equipment.

5.1 SUMMARY

The economic analysis was built on our experience with tabbing and connecting thick (≥ 300 μm silicon) cells. This experience was used to generate the cost analysis of Section 3 that clearly points to the importance of improvements in yield and throughput to make PV manufacturing more cost effective. **This cost effectiveness is achieved through the incorporation of higher process yield and throughput of thinner silicon cells than is presently achieved.** In particular, the analysis points to the handling intensive areas of tabbing and stringing as two significant cost drivers.

This cost significance of tabbing and stringing led to the conceptualization of an advanced connecting machine. Section 4 detailed the design concepts and guidelines. The initial design utilizes the experience Spire has obtained over the last seven years in the production of tabbing equipment. The design stresses a modular and flexible nature, so as to assure the capability of tailoring the machine to all manufacturers.

5.2 FUTURE DIRECTION

We have entered into initial discussions with several present manufacturers about the utility of the connecting equipment. There has been preliminary interest in the possible teaming between Spire and one of these manufacturers towards the development of this machine. It is our intent to continue with the development of the machine in a proposed Phase II of the PVMaT program. In order to demonstrate the capabilities of such equipment, it will be necessary to install the equipment into a production environment; hence the teaming approach. The successful demonstration of the equipment will allow Spire to manufacture similar equipment for the use of the U.S. industry, to thus enhance the position and cost-effectiveness of the U.S. PV manufacturing base.

SECTION 6

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The work performed in this contract was focused on two areas: an economic analysis of present manufacturing methods and the conceptualization of advanced equipment. The economic analysis was built on our experience with tabbing and connecting thick cells. This experience was used to generate the cost analysis that clearly points to the importance of improvements in yield and throughput to make PV manufacturing more cost effective.

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